

Persistence of black holes through a cosmological bounce

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Abstract

We discuss whether black holes could persist in a universe which recollapses and then bounces into a new expansion phase. Whether the bounce is of classical or quantum gravitational origin, such cosmological models are of great current interest. In particular, we investigate the mass range in which black holes might survive a bounce and ways of differentiating observationally between black holes formed just after and just before the last bounce. We also discuss the consequences of the universe going through a sequence of dimensional changes as it passes through a bounce.

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In some cosmological scenarios, the universe is expected to recollapse to a big crunch in the future and then bounce into a new expansion phase. The evidence that the universe is currently accelerating does not exclude this possibility if the acceleration is driven by a scalar field rather than a cosmological constant [1]. Even if the universe is destined to expand forever, its present expanding phase may have been preceded by the collapse and bounce of an earlier universe. Both past and future bounces would arise in cyclic models but not all bouncing models are cyclic.

As regards the bounce mechanism, even classical general relativity (GR) permits a turnaround if one invokes a positive cosmological constant [2], although this simple option is not favoured by current observations. Other possible mechanisms are based on alternative theories of gravity (such as higher derivative theories [3]) which lead to a modified Friedmann equation. A bounce can also occur within theories of quantum gravity, such as string theory [4], where it has been dubbed the “big bounce” within the *pre-big-bang* scenario [5], loop quantum gravity (LQG), where both black hole and cosmological singularities may be resolved [6], or quantum cosmology [7]. The bounce density would most naturally have the Planck value in quantum gravity but it could be sub-Planckian in some string scenarios or if one invokes a classical mechanism.

Cyclic models were included even in the original Friedmann paper [8], although without specifying any bounce mechanism. A more physical GR model was proposed by Tolman [9], in which extra entropy is generated at each bounce, leading to universes which attain progressively larger size at maximum expansion. LQG versions of this type of model might allow the universe to eventually escape the cyclic phase and enter a final de Sitter period [10]. Another interesting scenario is *cyclic brane cosmology* [11], in which the universe undergoes a periodic (and classically eternal) sequence of big bangs and big crunches, each one being associated with the collision of two 3-branes in a fourth spatial dimension. Each bang results in baryogenesis, dark matter production, nucleosynthesis, galaxy formation, an epoch of low-energy acceleration, and finally a contraction that produces homogeneity and flatness in the

next cycle. There is no inflation but the dynamical behavior in the final phase of each cycle is supposed to explain many of the observational features usually attributed to inflation. The nature of the fluctuations generated by quantum perturbations in this model has been studied in [12].

Whatever the scenario, black holes would be an important probe of a cosmological bounce, just as primordial black holes (PBHs) provide an important probe of the early stages of the standard big bang [13]. However, the issues raised are somewhat different for future and past bounces. Both scenarios raise the question of whether black holes formed in one universe can persist into the next but the existence of a past bounce directly impinges on observations. In particular, we need to distinguish between black holes which formed *during* the big crunch (i.e. because of it) and those that formed *before* it. We refer to these as “big-crunch black holes” (BCBHs) and “pre-crunch black holes” (PCBHs), respectively. It is not clear whether any observations could distinguish between black holes which form just before the bounce (i.e., in the final moments of the big crunch) or just afterwards (i.e., in the first moments of the big bang), since both types of black holes would have comparable mass ranges.

Future bounces are obviously not relevant to current observations but they raise the mathematical issue of what is meant by a black hole in recollapsing universes. Since these have closed spatial hypersurfaces, there is no asymptotic spatial infinity, so the whole universe is in a sense a black hole and each black hole singularity is part of the future big crunch one. By contrast, the black hole singularity in an ever-expanding model is not part of any cosmological singularity. Of course, all singularities may be removed in a bouncing model.

Let us first consider the mass range in which black holes can form in a bounce. We assume that the universe bounces at some density ρ_B , which might either be of order the Planck density, $\rho_P \sim c^5/(G^2\hbar) \sim 10^{94} \text{g cm}^{-3}$, or much less. A spherical region of mass M becomes a black hole when it falls within its Schwarzschild radius, $R_S = 2GM/c^2$. At this point the collapsing matter has density $\rho_{BH} = (3M/4\pi R_S^3) \sim 10^{18}(M/M_\odot)^{-2} \text{g cm}^{-3}$ from the

perspective of an external observer, although the matter itself collapses to a greater density. A BCBH can presumably only form if its density is less than ρ_B , and this corresponds to a *lower* limit on the black hole mass $M_{\min} \sim (\rho_P/\rho_B)^{1/2} M_P$, where $M_P \sim 10^{-5}\text{g}$ is the Planck mass. This corresponds to the bold line on the left of Fig. 1. BCBH formation is not guaranteed by the density alone, since one would expect it to require inhomogeneities or some form of phase transition. However, it is possible that the black hole nucleation rate might become very high at the Planck temperature for quantum gravitational reasons.

There is also a mass range in which pre-existing PCBHs lose their individual identity by merging with each other prior to the bounce. If the fraction of the cosmological density in these black holes at the bounce epoch is f_B , then the average separation between them is less than their size (i.e. the black holes merge) for $M > f_B^{-1/2} M_{\min}$. This condition can also be written as $f_B > (M/M_{\min})^{-2}$. Since f_B cannot exceed 1, there is a always range of masses in which BCBHs may form and PCBHs do not merge. If the PCBHs do merge, this will initially generate holes with a hierarchy of masses larger than M but eventually the universe will be converted into a homogenous vacuum state apart from the sprinkling of singularities (or “Planck balls”) generated by the original collapsing matter.

Unless the universe is always matter-dominated, one must distinguish between f_B and the *present* fraction f_0 of the universe’s mass in black holes. The ratio of the matter to radiation density scales as the cosmic scale factor R , so this will decrease during collapse and increase during expansion in a radiation-dominated era. If ρ_0 and ρ_{rad} are the *current* densities of the matter (including black holes) and cosmic background radiation, matter-radiation equality therefore occurs when $R_{eq}/R_0 = \rho_{rad}/\rho_0 \sim 10^{-4}$. This corresponds to a density $\rho_{eq} \sim 10^{12}\rho_0 \sim 10^{-17}\text{g cm}^{-3}$ and this applies in either a contracting or expanding phase. The fraction of the universe in black holes at a radiation-dominated bounce is therefore $f_B \approx f_0 (\rho_{eq}/\rho_B)^{1/4}$, so the merger condition becomes $f_0 > (M/M_{\min})^{-2} (\rho_B/\rho_{eq})^{1/4}$. Substituting for M_{\min} and ρ_{eq} gives $f_0 > 10^{28} (\rho_B/\rho_P)^{-3/4} (M/M_P)^{-2}$, corresponding to the bold line on

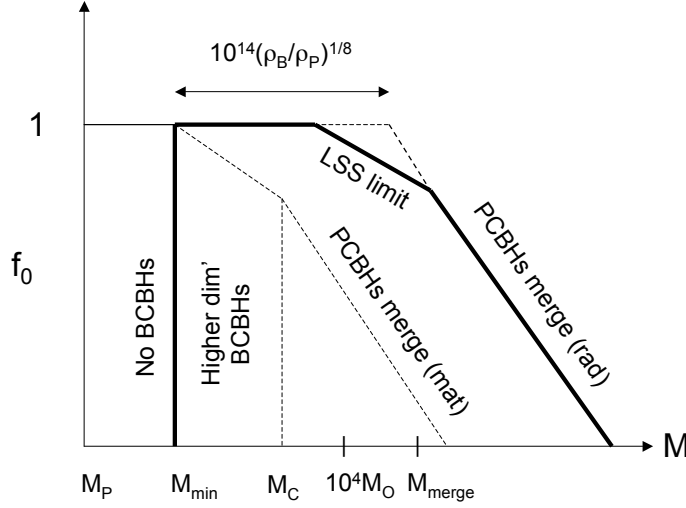


Figure 1: This shows the domain in which black holes of mass M containing a fraction f_0 of the present density can form in the big crunch or avoid merging if they exist before then.

the right of Fig. 1. Equivalently, $M > 10^{14} f_0^{-1/2} (\rho_P / \rho_B)^{3/8} M_P$.

There are various dynamical constraints on the form of the function $f_0(M)$ for PCBHs which are non-evaporating (i.e., larger than $M_* \sim 10^{15} \text{g}$) [13]. The most obvious one is that non-evaporating black holes must have $f_0 < 1$ in order not to exceed the observed cosmological density and this gives a minimum value for the merger mass. We can express this as $M_{\text{merge}} \sim 10^9 (t_B / t_P)^{3/4} \text{g}$, where t_B is the time of the bounce as measured from the notional time of infinite density. This is around 10^{15}g for $t_B \sim 10^{-35} \text{s}$ but as large as $1 M_\odot$ for $t_B \sim 10^{-13} \text{s}$ or $10^4 M_\odot$ for $t_B \sim 10^{-5} \text{s}$, so the observational consequences would be very significant. Note that the density of the universe when the black holes merge is much greater than it is when they form. Another important dynamical constraint is associated with large-scale structure (LSS) formation deriving from Poisson fluctuations in the black hole number density [14]. Applying this argument to the formation of Lyman- α clouds gives $f_0 < (M / 10^4 M_\odot)^{-1}$ [15], implying an upper limit of $10^4 M_\odot$ on the mass of any black holes which provide the dark matter. These limits are shown by the bold lines at the top of

Fig. 1. We note that in some quantum gravity models, the complete decay of black holes is prevented, leading to stable remnants with around the Planck mass. This leads to a limit $f_0 < (M/M_P)$ over some range of M but this is not shown explicitly in the figure.

One important observational issue is whether it is possible to differentiate between black holes formed just before and after the bounce. In the standard non-bouncing scenario, PBHs generated *before* inflation are exponentially diluted, so PBHs present today are usually assumed to form at the *end* of inflation. In a bouncing model, unless there were a matching deflationary period in the collapse phase, any BCBHs would also be exponentially diluted. On the other hand, there is no inflation in the expanding phase of some bouncing models. Another difference concerns the relative importance of accretion and evaporation. Accretion is negligible in the expanding phase but may not be in the collapsing phase and this could block evaporation altogether. If evaporation does occur, it would be on a much longer timescale than the black hole formation time and so would occur after the bounce, whenever the black holes form.

It is possible that the universe gains an extra spatial dimension – or goes through a sequence of dimensional increases – as it approaches the big bang in the past or the big crunch in the future. The scale of the extra dimension, R_C , would most naturally be comparable to the Planck length but it could be much larger, and the time of the transition (measured notionally from the time of infinite density) would be $\tau_C \sim R_C/c$. The associated density is then $\rho_C \sim c^2/(GR_C^2)$, which is less than the bounce density (so that higher-dimensional effects are important) for $R_C > c(G\rho_B)^{-1/2}$. At larger densities both the matter content and any black holes must be regarded as higher dimensional.

If there are $3 + n$ spatial dimensions and the black hole is spherically symmetric in all of them, then the radius of its event horizon becomes $R_S \sim (M/M_C)^{1/(n+1)} R_C$, where $M_C \sim c^2 R_C/(2G)$ is the mass at which the dimensional transition occurs. Thus $R_S \propto M$ for $n = 0$ and $R_S \propto M^{1/2}$ for $n = 1$. For $M < M_C$, the higher-dimensional density required

for black hole formation is $\rho_{BH} \propto M^{-2/(1+n)}$, so the lower limit on the BCBH mass becomes $M_{\min} \sim (\rho_P/\rho_B)^{(1+n)/2} (R_P/R_C)^{n(3+n)/2} M_P$. The black hole merger condition becomes $f_B > (M/M_{\min})^{-2/(1+n)}$, which is further modified if the universe is dominated by its higher-dimensional matter content when it bounces. Conceivably, the change in dimensionality could itself trigger a bounce.

To conclude, we have discussed whether black holes in some mass range could persist in a universe which recollapses and then bounces into a new expansion phase. We find that there is a range of masses in which BCBHs form and PCBHs do not merge but these limits are modified by the inclusion of radiation and the effects of extra dimensions. The consequences of such black holes, only some of which have been discussed here, provide an important signature of bouncing cosmologies, which allows them to be falsified by observations. One problem which has stymied the success of cyclic models is that the formation of large-scale structure and black holes during the expanding phase leads to difficulties during the contracting phase [9]. This may be related to the second law of thermodynamics because unless the black holes are small enough to evaporate via Hawking radiation, the area theorems imply that they grow ever larger during subsequent cycles. Understanding the persistence of black holes through a bounce is clearly relevant to this problem.

Finally, some of these arguments may also pertain in cosmological scenarios which do not involve a bounce. For example, in the *cosmological natural selection* scenario, black holes evolve into separate expanding universes and this means that the constants of physics evolve so as to maximize the number of black holes [16]. This raises the issue of whether the persistence of black holes is related to the second law of thermodynamics. In the *conformal cyclic cosmology*, there exists an unending succession of aeons and our big bang is identified with the conformal infinity of the previous one [17]. Numerous supermassive black hole encounters occurring within clusters of galaxies in the previous aeon would yield bursts of gravitational radiation and these would generate randomly distributed families of concentric circles in the CMB sky over which the temperature variance is anomalously low [17].

References

- [1] R. Caldwell, Phys. Lett. B. **545**, 23 (2002).
- [2] G. Lemaitre, Mon. Not. R. Astron. Soc. **91**, 490 (1931)
- [3] M. Novello and S. Bergliaffa, Phys. Reports. **463**, 127 (2008).
- [4] N. Turok, M. Perry and P. Steinhardt, Phys. Rev. D **70**, 106004 (2004).
- [5] G. Veneziano, Europhys. Lett. **2**, 133 (1986).
- [6] M. Bojowald, Phys. Rev. Lett. **86**, 5227 (2001) & Phys. Rev. Lett. **95**, 091302 (2005);
A. Ashtekar, T. Pawlowski and P. Singh, Phys. Rev. D **74**, 084003 (2006).
- [7] J. B. Hartle and S. W. Hawking, Phys. Rev. D. **28**, 2960 (1983).
- [8] A. Friedmann, Zeitschrift fr Physik **10**, 377386 (1922).
- [9] R. Tolman, *Relativity, Thermodynamics, and Cosmology* (Oxford, Clarendon, 1934).
- [10] D. J. Mulryne *et al.*, Phys. Rev. D. **71**, 123512 (2005).
- [11] P. J. Steinhardt and N. Turok, Phys. Rev. D **65**, 126003 (2002); J. Khoury, P. Steinhardt, and N. Turok, Phys. Rev. Lett. **92**, 031302 (2004).
- [12] J. L. Lehnars *et al.*, Phys. Rev D **76**, 103501 (2007); Y. Cai *et al.* [arXiv:1101.0822].
- [13] B. J. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, Phys. Rev. D. **81**, 104019 (2010).
- [14] P. Meszaros, Astron. Astrophys. **38**, 5 (1975); B. J. Carr, Astron. Astrophys. **56**, 377 (77).
- [15] N. Afshordi *et al.*, Ap. J. **594**, L71 (2003).
- [16] L. Smolin, Class. Q. Grav. **9**, 173 (1992).
- [17] R. Penrose, *Cycles of time: An extraordinary new view of the universe* (Bodley Head, London, 2010); V. G. Gurzadyan and R. Penrose, arXiv:1011.3706.